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AN ANALYSIS OF A RETROGRADE DEPRESSION IN THE EASTERN UNITED STATES OF AMERICA

By J. BJERKNES, Bergen, Norway, and M. A. GIBLETT, London, England

The present investigation was carried out during a brief visit of the writers to the United States Weather Bureau, Washington, in the late summer of 1924. A study of the working charts in the forecast division of the Bureau suggested that a detailed examination of specially selected cases would yield interesting results, especially as the Weather Bureau possesses a very complete set of autographic records of meteorological elements at a great number of stations. The investigation of the present case was rendered possible through the courtesy and assistance of Dr. C. F. Marvin, chief of bureau, and of members of his staff, to whom we wish at once to express our gratitude.

The depression of October 22–25, 1923, was selected as it represented an interesting case of a retrograde depression, or one which had a westward component in its motion. Such systems are comparatively rare in Europe, and they are extremely rare in the northeastern United States. This paper contains no new theory, but the results of the investigation are satisfactory in that they show that an American retrograde depression exhibits the same structure as is familiar in the case of the European ones.

The situation during the early stages of the depression is given by the two maps in Figures 1 and 2. The first of these shows two anticyclones, a cold continental one centered over the northern United States, and a warm one centered over the ocean east of Bermuda. A long, narrow trough of relatively lower pressure lies between them, some 300 miles off the coast. The lowest pressure in this trough, 1,007 millibars, is found at Nassau, in the Bahamas. The trough is seen to mark a sharply defined limit between two distinct air currents. On the eastern side is a warm southerly current of evident tropical origin, with a fairly homogeneous temperature, in most places above that of the sea. On the other side, there is a colder northeasterly current originating beyond the northern boundary of the chart. The temperature in this current increases toward the south as the air passes over warmer and warmer water, but it has the usual characteristic of the temperature of "polar air" moving southward in that it remains everywhere below that of the sea. Even in the extreme south it shows a deficit of as much as 7° or 8° F. Throughout the tropical current the weather is generally fair, even close to the trough, whereas on the other side of the discontinuity the sky is uniformly overcast for a distance of about 400 miles, and rain is falling in a zone 200 to 300 miles broad, extending from Florida to Nova Scotia. We have here a case of approximate equilibrium between two adjacent counter-currents separated by an inclined plane sloping upward over the colder air at an angle with the ground, which is given by the classical formula of Margules.[1] The occurrence of precipitation in a continuous band on the cold side of the discontinuity shows, however, that the warm air is already mounting the inclined plane above the cold air, representing a first departure from equilibrium conditions.

The chart for the next morning, Figure 2, shows that 24 hours later the discontinuity has become distorted, the portion between latitudes 32° north and 39° north having advanced about 150 miles towards the coast. In the field of pressure, this appears as the formation of an elongated depression with its center in about latitude 33° north at the sharpest bend in the discontinuity. The barometric pressure in the center is 1,000 millibars, lower than any pressure on the previous chart, so that we have here the phenomenon of the development of a depression on a *preexisting* discontinuity between adjacent warm and cold air masses. The deepening of the depression has synchronized with increasing wind velocities, Beaufort force 11 being reported by one ship off Cape May, N. J. The depression has a well-defined "warm sector" which has only broken skies and no rain, except close to the center. On the other hand, the cold portion continues to have an extensive rain area, now of characteristic form, broad north of the center where the discontinuity behaves as a "warm front," and narrower to the south where it takes on the character of a "cold front."[2]

The further history of the system has been traced in much more detail by the close study of autographic records of wind, temperature, pressure, sunshine and rainfall from the complete network of land stations, particularly by hourly weather charts constructed from these records. While this was necessary for the complete diagnosis of the case, it is impossible to reproduce all these maps and registrations in this brief account. A selection has accordingly been made, comprising the four maps in Figure 3, for the epochs October 23, 8 p. m. (75th meridian time), October 24, 8 a. m., and 8 p. m., October 25, 8 a. m., and registrations at 18 stations in Figure 5.

On the first chart of Figure 3, for the evening of October 23, the center has just crossed the coast and is to be found a little to the north of Norfolk, Va. The temperature at Cape Henry, just to the east of the center is 65° F., showing the arrival of the tropical air, which has, however, been chilled somewhat by contact with the colder coastal waters.

On the morning map for October 24, the center of the depression is on the point of passing the Alleghenies, in the well-known way of crossing a mountain range by developing a new center on the further side, while the original center decays. The tropical air can now no

[1] Margules. Hann-Band der Met. Zeitschr. 1906. p. 293.
[2] J. Bjerknes and H. Solberg. Geofysiske Publikationer, Vol. III., No. 1, Kristiania, 1922. (Abstract in Monthly Weather Rev., Sept., 1922)

longer be regarded as extending to the center of the depression, but only to the vicinity of New York. Between New York and the center of the system the tropical air is occluded, in other words lifted completely off the surface between the cold air arriving from the northeast and a branch of the same air mass, which has had time to curve round the depression and arrive back, from the south. This view is supported by the construction of the trajectories of air masses in different parts of the depression. (See fig. 4.) In doing this work the hourly maps referred to above were brought into use. Taking the air mass at New Haven on the morning of the 24th with a temperature of 50° F. and tracing it back, it is found to have entered the depression from the region of Nova Scotia, thus being of a cold origin. The air mass over Sandy Hook on the morning of the same day has a temperature of 60° F. and may nevertheless be traced back to a similar northern source. It has, however, in the meantime, traversed a curved path, encircling the center of the depression and leading down to latitude 37° before recurving. This offers more opportunity for the air to become warmed than is the case for the first

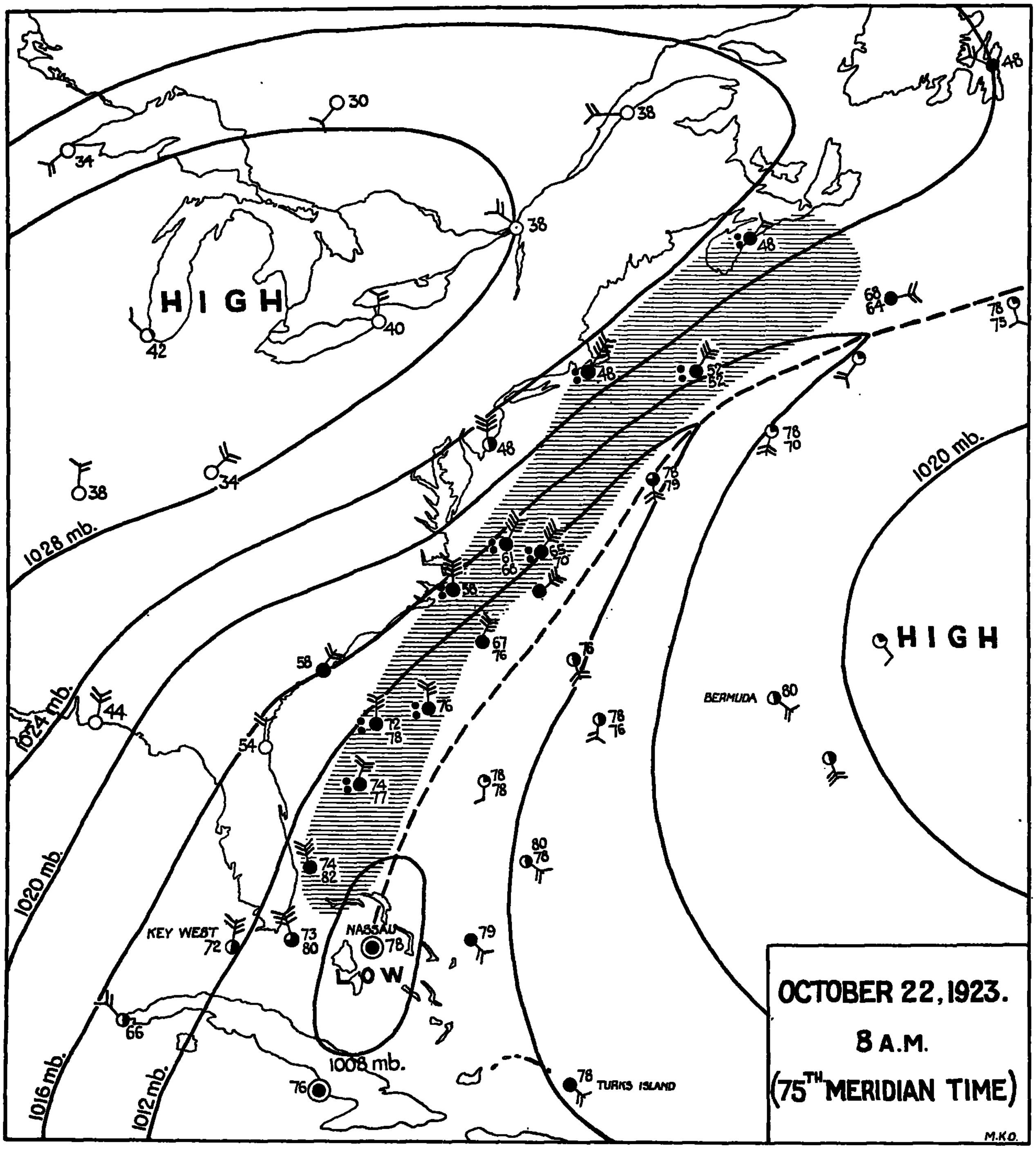

FIG. 1.—Map showing conditions during early stage of depression. (In this and later figures the following symbols are used: The Beaufort force of the wind is indicated by the number of feathers on the arrows; the amount of sky covered by cloud is given by the fraction of the circles shaded; precipitation at a station is shown by two dots; areas where precipitation is taking place are shaded; figures indicate temperatures in degrees F., and where, in the case of ships, two are given together, the lower refers to the sea; "warm fronts" are indicated by lines composed of dashes and "cold fronts" by lines composed of dots.)

path considered. The observed contrast of temperature along the occluded portion of the "front" is thus quite natural. It is, however, interesting to remark that nearer the center the circulating air is not carried so far south, so that the contrast diminishes. (The southeast wind at Harrisburg, Figure 3b, has a temperature of depression, although its temperature of 60° F. is not higher than that of Sandy Hook. The presence of fog at Block Island is here significant and is consistent with the southern origin of the air. The latter, in passing northwards, has been cooled below its dewpoint on reaching the rather cold water near the coast. The

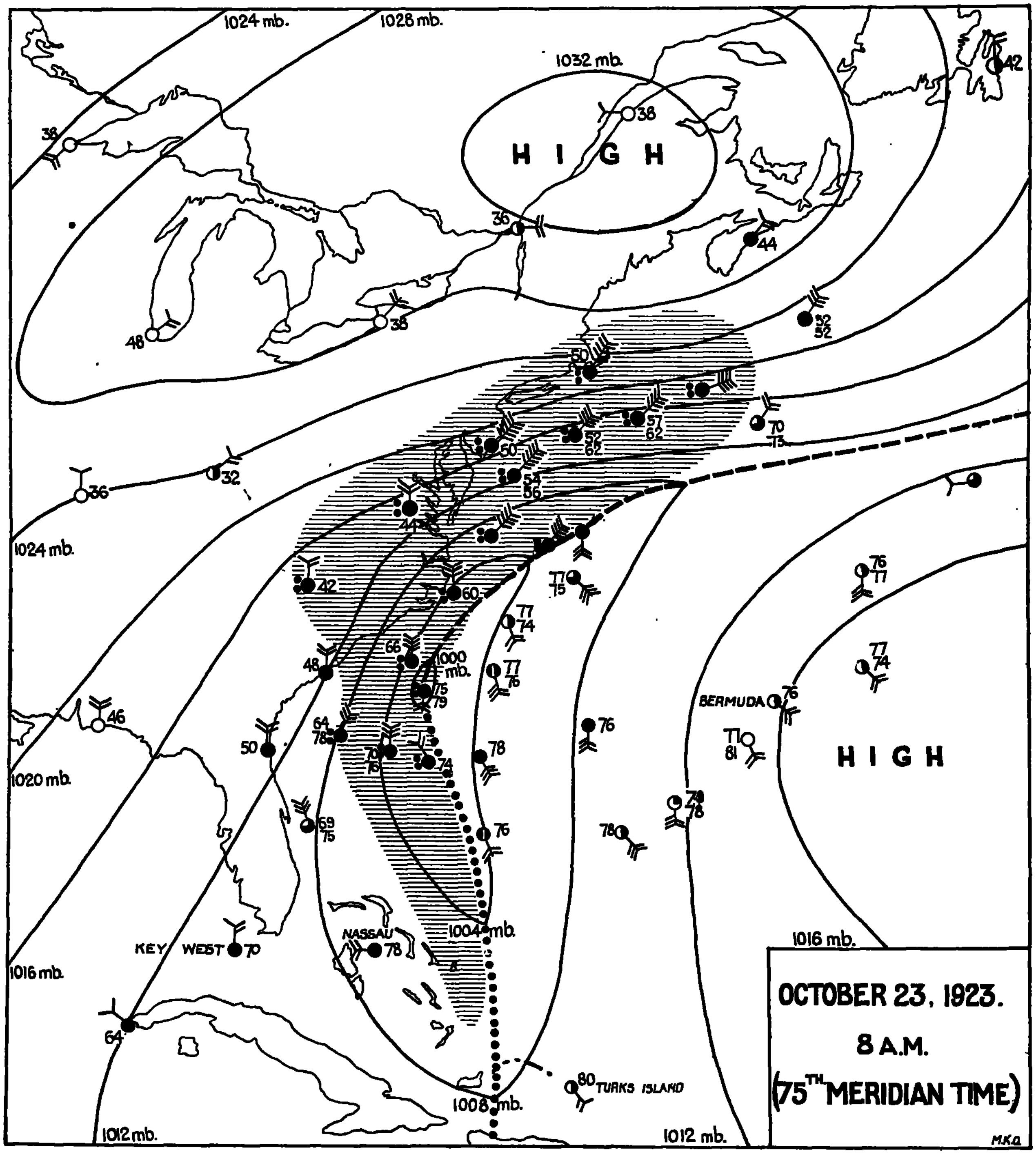

Fig. 2.—Map showing depression during course of development

only 52° F.). The third trajectory of Figure 4, shows the path of the air mass arriving at Block Island at the same time as the masses already considered arrive at New Haven and Sandy Hook. This trajectory leads directly back to the tropical current in the region of Bermuda, thus defining the air of Block Island as belonging, without any doubt, to the "warm sector" of the average October water temperature in this vicinity is 59° F., and in November the temperature is already down to 53° F., so that at the date in question it must be about 57° F.

This cooling of the air must necessarily be confined to a shallow surface layer. Above the cooled layer the original temperature of the tropical current must persist, apart from slow changes by radiation effects. It will be seen later, when the registrations are discussed, that the cooled layer is so thin as to be readily destroyed by some hours' sunshine. The presence of this cooled layer has allowed for in analyzing a situation from surface data alone, since they mask conditions in the upper air.

The evening map for October 24 shows the arrival of the foggy tropical current on the coast of Maine. The

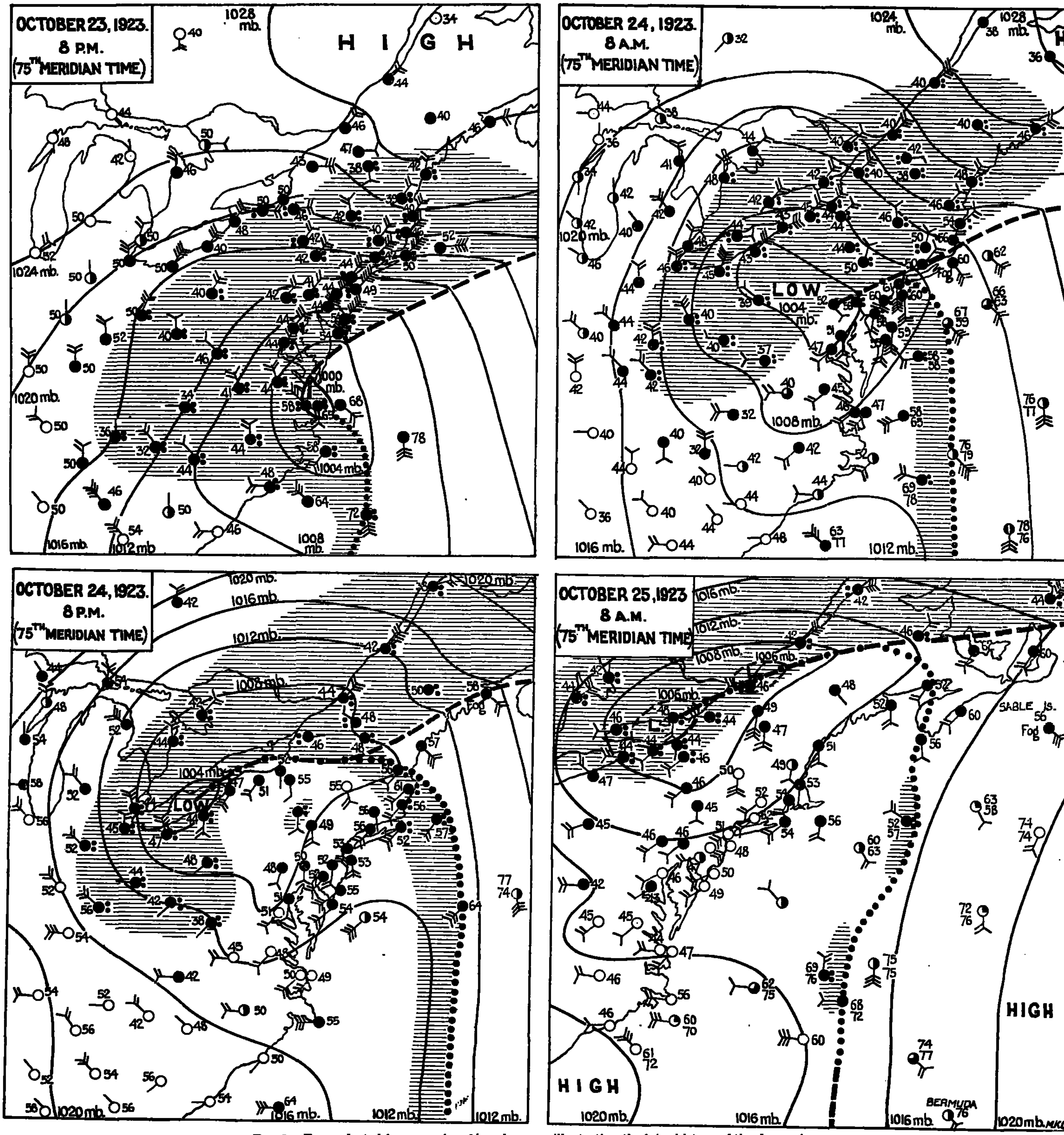

FIG. 3.—Four selected from a series of hourly maps illustrating the later history of the depression

therefore very little importance in connection with the mechanics of the depression, which depends for its supply of energy upon temperature contrasts between air masses of great vertical extent. Such effects as this must be temperatures at Eastport, 59° F., and Portland, 57° F., have risen 12° and 9°, respectively, since the morning, with the passage of the "warm front." A rise in the surface temperature beyond these figures is checked by the presence of cold water, the average temperature of which is about 52° F. at this period of the year. The relatively colder current from the southwest has advanced past Nantucket, and the "cold front" now lies almost wholly over the sea.

The rain area assumes on this, as on the previous chart, a mushroom shape, rather typical of this stage of development. The "cold front" rain forms the stalk, and the "warm front" rain, together with the extension along the occluded portion of the front, forms the head.

On the morning of the 25th, foggy conditions still prevail at sea in the "warm sector," as shown by reports from Halifax and Sable Island. The position of the "warm front" is well defined by the temperatures 60° F. at Sydney and 44° F. at Port aux Basques, with opposing winds, and equally by the temperatures 62° F. at Charlottetown and 46° F. at Chatham, again with opposing

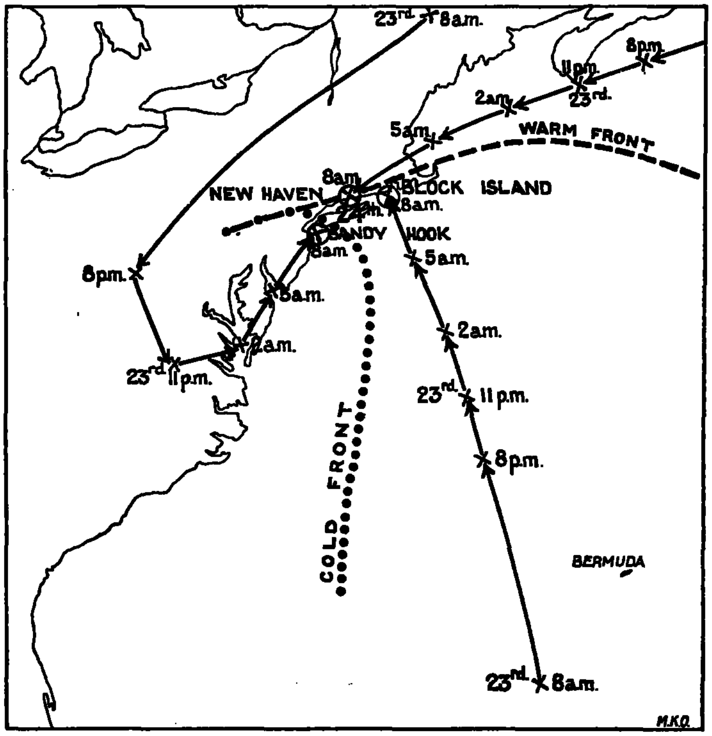

FIG. 4.--Diagram showing the trajectories of the air masses which arrived at New Haven, Sandy Hook, and Block Island at 8 a. m. October 24, 1923

winds. The "cold front" has, during the night, advanced from Nantucket to the western point of Nova Scotia. In the southern part, south of latitude 40°, the front has become almost stationary, the cold air tending to spread out laterally north and south instead of advancing east. Conditions are now favorable for the formation of a new depression on the reestablished stationary front, and the southernmost part of all seems already to retire again in a westward direction as a "warm front." Along the portion of the front over the ocean the rain area is apparently breaking up.

Passing now to the conditions at individual stations, these are represented in graphical form in Figure 5. The stations are arranged in three columns, each column corresponding to one of the dotted lines on the inset map and giving a section across the track of the depression. Let us consider first the stations in the first column, passed by the depression when at maximum development. The thermogram for Cape Henry exhibits a very clearly defined "warm sector" from 6 to 9 p. m. on October 23. The diagram also shows that before this period the wind is NE., during the warm interval it is from a southerly point, and finally becomes SW. when the "cold front" arrives. It is also seen that continuous rain falls while the wind is NE., that in the "warm sector" there is only a trace of rain, not sufficient to register, and that, with the arrival of the SW. wind, the rain again becomes measurable but does not last very long. It is interesting to notice also that the next day, although sunny, has a maximum temperature 10° lower than that during the dull weather of the day under discussion. The rounded form of the thermogram appropriate to the local diurnal heating of October 24 may be contrasted with the more abrupt shape of that representing the advectively transported warmth of October 23, which is quite independent of diurnal effects, and in this case occurred in the evening.

Norfolk, which is only 16 miles from Cape Henry, happened to be on the other side of the track of the depression, the wind turning gradually from NE. through NW. and W. to SW. The Norfolk thermogram shows only a gradual rise of temperature reaching 58° F. when the depression is nearest, whereas the Cape Henry curve shows, in addition to this, the further sharp rise in the evening to 65° F. due to the "warm sector." After this time the thermograms are again almost identical. Further to the west, at Richmond and Lynchburg, we have other thermograms typical of the left side of the track. Here the curves are almost flat during the passage of the depression, while, in common with Norfolk and Cape Henry, the normal diurnal variation reappears the next day, after the clearing has set in.

It still remains to explain why the temperature at Norfolk in the northeast current gradually rose, giving what might at first sight be mistaken for a passage of the "warm sector." The present material of surface observations can not itself give any definite answer, but we may refer to the explanation given by Stüve [3] of the same phenomenon in Europe, on the basis of aerological observations. According to him the rise of temperature in the cold air adjacent to the discontinuity is an adiabatic rise due to the sinking and lateral spreading of this air in the wedge underlying the air of the warm sector. The general type of thermogram for the passage of a "warm front" is, accordingly, a gradual slow rise of temperature followed in most cases by a discontinuous upward jump. Cape Henry is of this type, a part of the gradual rise coming, however, before 8 a. m. on October 23, and so not being shown in the diagram. Much more striking examples are given by Boston, Hartford, New Haven, etc. In the case of a station slightly to the left of the track of the depression the gradual rise appears without the further "warm sector" rise. This is exemplified by Norfolk, and, less strikingly, by Washington. Stations more remote from the track on the left-hand side do not come within the range of the adiabatic warming effect at all.

Following the coast stations northward, we find that Atlantic City and Sandy Hook have thermograms very similar to that of Cape Henry, and even the maximum temperature arrived at within the "warm sector" is the same within one degree, although this maximum occurred in the evening at Cape Henry, during the night at Atlantic City, and in the morning at Sandy Hook. Baltimore, nearer to the track of the depression, has a very short period of high temperature, reaching a sharp

[3] "Aerologische Untersuchungen zum Zwecke der Wetterdiagnose" Die Arbeiten der Preussischen Aeronautischen Observatoriums XIV Band, 1923.

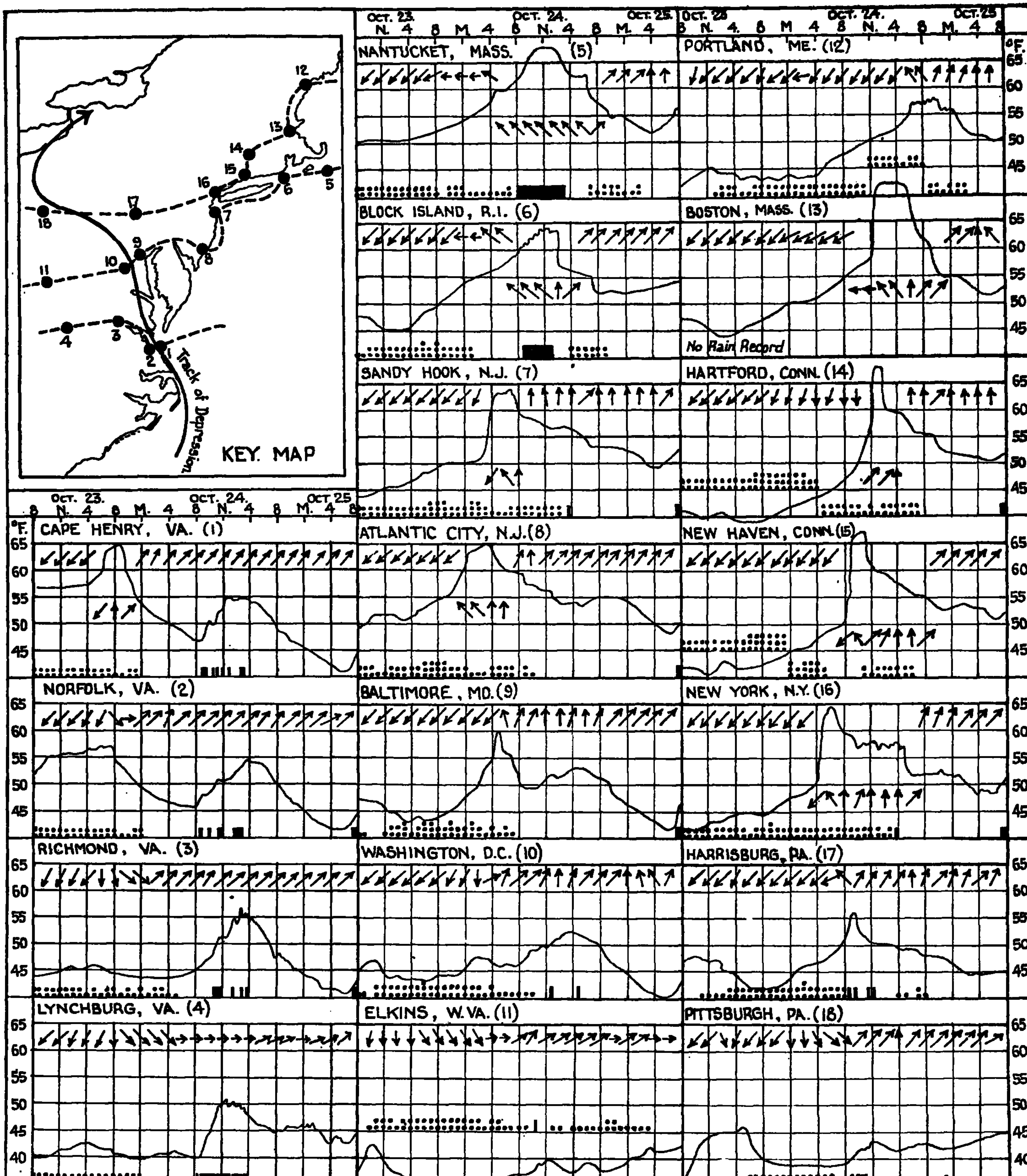

FIG. 5.—Diagram prepared from the autographic records at 18 selected stations in the area under consideration. (The arrows show the wind direction at intervals of two hours The dots indicate the rainfall during the preceding hour, one dot meaning a trace only, two dots amounts up to 0.20 inch, three dots amounts of 0.20 inch or above. Periods of sunshine are indicated by black areas on the same horizontal line as the rainfall. The numbers placed after the station names correspond to the inset key map.)

maximum of but 60° F. This evidently represents the type of thermogram which must be obtained during the transition to an "occlusion," when the warm sector is on the point of disappearing from the surface. The sharp maximum in the Baltimore thermogram is entirely absent from the Washington record obtained less than 40 miles away, but on the other side of the track, while the other portions of the curve are very similar at both places.

The longest duration of the "warm sector" is to be found on the two stations Block Island (4 a. m.–2 p. m.) and Nantucket (4 a. m.–6 p. m.). Although situated not more than 80 miles apart, these two stations have rather different thermograms during the time the warm sector passes. This may, however, be accounted for when considering the local conditions at both stations. Whereas the station at Block Island is situated on a very small island, Nantucket lies on a larger one, and—what is in this case of special importance—on the northwestern side of the island.

As we have already mentioned, the warm sector current from the southeast contained a shallow fog layer produced by the cooling in contact with the cold coastal waters. This fog must dissolve again when arriving over land, especially if the higher cloud layers break up so as to expose the fog layer to direct insolation. This is the phenomenon which we may observe on Block Island and Nantucket. At the latter place, where the air has passed over land surface before reaching the station, the fog vanishes shortly after sunrise, and the temperature rises, under the influence of insolation, to 68° F. At the former, the fog does not dissolve until some two or three hours after sunrise, and the structure of the curve—rapid small temperature fluctuations—is a sign of alternate heating by the sun and cooling as new fog patches drift over. It is not until the last half of the warm sector that the fog disappears perfectly, unveiling the almost cloudless sky, which was characteristic of the tropical current on the first maps considered. (Figs. 1 and 2.)

The cold front leaves a very marked trace on the thermograms (Block Island 2 p. m. and Nantucket 6.30 p. m.). The arriving cold wedge has apparently a rather gentle slope as it is not until some time after the cold front passage at the ground that the warm air has been lifted sufficiently to give precipitation. Once started, however, the rain lasts rather long.

Boston, Hartford, New Haven, and New York provide good examples of thermograms with the passage of a "warm sector," the maximum temperatures reaching (partly assisted by the diurnal effects) 70° F., 68° F., 67° F., and 65° F., respectively. Portland represents the same type with, however, a markedly depreciated warm sector temperature on account of the fog. Harrisburg represents the type of thermogram to be expected at the place where the warm sector air has just been lifted away from the ground, and Pittsburgh (on the western side of the track) shows the presence of rather uniformly cold air during the whole cyclone passage.

The complete mechanism of the depression in all layers, the rules for its growth, propagation, etc., can of course not be analyzed without an additional aerological diagnosis. In the absence of adequate information of this kind we must confine our attention to the conclusions as to the mechanism of our retrograde depression which may be drawn merely from surface observations. The results, which may seem partly hypothetical, receive, however, additional support from their concordance with those of numerous other cases.

The movement of the depression, although surprising when considered in relation to average tracks, appears quite normal when it is seen in relation to its thermal structure. The motion of the center is, at each moment, approximately parallel to the instantaneous direction of the warm current. It is this current which decides the displacement of the extremity of the warm tongue where the lowest pressure is located. The warm current in the present case is originally from almost due south, but later acquires a component from the east, at the time when the depression curves toward the northwest. (See track, fig. 5.)

The depression continues its northwestward propagation also after the warm air has been lifted off the ground, probably governed by the southeast current of a still existing "upper warm sector." This view is also confirmed by the fact that the upper clouds in front of the depression were moving from southeast. From the moment when the warm air nearest the center is lifted away from the ground the depression begins to fill up, being from now deprived of the supply of potential energy—in the form of temperature contrasts—for the maintenance of its kinetic energy. Farther east, where the "warm sector" still exists, potential energy is still available and gives rise to the formation of a secondary depression. The first sign of it is to be seen on Figure 3b in the region of New York, at the extremity of the warm tongue. The formation is more accentuated the next day over northern Massachusetts and reaches finally the stage of an independent center between Montreal and Quebec on the morning of the 25th. This center from now on becomes the main one, and the dying "mother cyclone" over Lake Ontario behaves as a secondary, while they both move off the map toward Labrador.

VARIATION IN SOLAR RADIATION INTENSITIES MEASURED AT THE SURFACE OF THE EARTH

551.52

By HERBERT H. KIMBALL

[Weather Bureau, Washington, Dec. 1924]

This paper brings up to date a communication on the same subject published in 1918.[1] For the years previous to 1901 no additional data are available. Revised data have been obtained for Warsaw, Poland, for the years 1901 to 1918, inclusive. Data have been added from Kew Observatory, England, for the years 1908 to 1921, inclusive, and from Helwan Observatory, Egypt, for the years 1914 to 1923, inclusive. The data for Washington, D. C., Madison, Wis., and Lincoln, Nebr., have been revised and brought down to the end of 1923. That for Santa Fe, N. Mex., ended with March, 1922.

In Table 1 there are given for each station the month and year of the beginning and ending of the record, and reference to a footnote giving the character of the data that have been made use of in this paper. In the previous paper it was noted that some of the records were fragmentary in character. There has been improvement in this respect in the records of later years.

The monthly normals of the solar radiation intensities for Kew Observatory and also for stations in the United

[1] Kimball, Herbert H., Volcanic eruptions and solar radiation intensities. MO. WEATHER REV., AUGUST, 1918, 46: 355–356.